SiC Power Devices for Applications in Hybrid and Electric Vehicles

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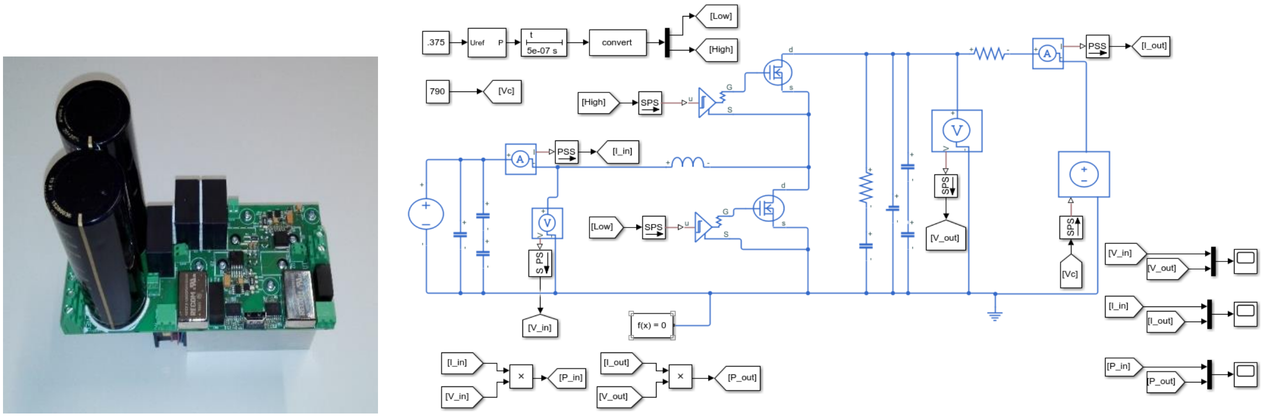
Abstract. Power electronic inverters and converters are an essential technology in the battery management and propulsion for Hybrid and Electric vehicles (HEVs). In order to improve competitiveness of HEVs there is a drive to improve the conversion efficiency of the power electronics. Using Silicon Carbide (SiC) power devices has been identified as a key enabler of future improvements in performance but it is essential to understand how these devices perform in an automotive context. Two similar half bridge circuits has been built using SiC MOSFETs, one with and the other without anti-parallel Schottky SiC diode. In this paper the power loss and efficiency of half-bridge has been compared as the dead-time is changed. Effect of changing dead-time on the converter are shown. The paper gives insight into these phenomena with additional experimental data supported by simulation. The implications for using SiC devices in both DC to DC and DC to AC converters are discussed.

Introduction

Hybrid and electric vehicles (HEVs) have achieved a growing market share over the past decade, with projections of 12.9 million electric cars by 2020 [1]. Power electronics is an essential technology for all these variants and there is a continuing drive for improvement in terms of improving conversion efficiency, increased power density, better reliability and increased operating temperature, all at reduced cost, to make HEVs a more attractive to consumers. For instance, improving the conversion efficiency of the power electronics translates into extended range. Employing silicon carbide (SiC) power devices has been identified as a key enabler of future improvements in performance and it essential to understand how these devices perform in an automotive context. To develop a high efficiency converter using SiC power devices it is very important to develop an accurate loss model, which is useful prior to the construction of the hardware itself. In literature, power loss models have been developed [2, 3]. However there is still an opportunity to develop improved methods for very accurately determining power losses.

In the author's previous work [4], the performance of this building block was investigated at different switching frequencies and varying temperatures over a wide input power. Both SiC MOSFETs and BJTs were studied and shown to give performance benefits compared to using conventional Silicon IGBTs. In this paper, the power loss and efficiency of a half-bridge intended both for use in DC to DC conversion and as a building block for a traction converter in HEVs is discussed. This converter uses SiC MOSFETs and investigation in conversion efficiency using external anti-parallel Schottky SiC diode or using built in diode has been compared as the dead-time is changed. The physical circuit and its schematic circuit diagram are shown in Fig. 1. The half bridge was operated in boost mode at a switching frequency of 100 kHz in the continuous mode converting between 550 V and 900 V.

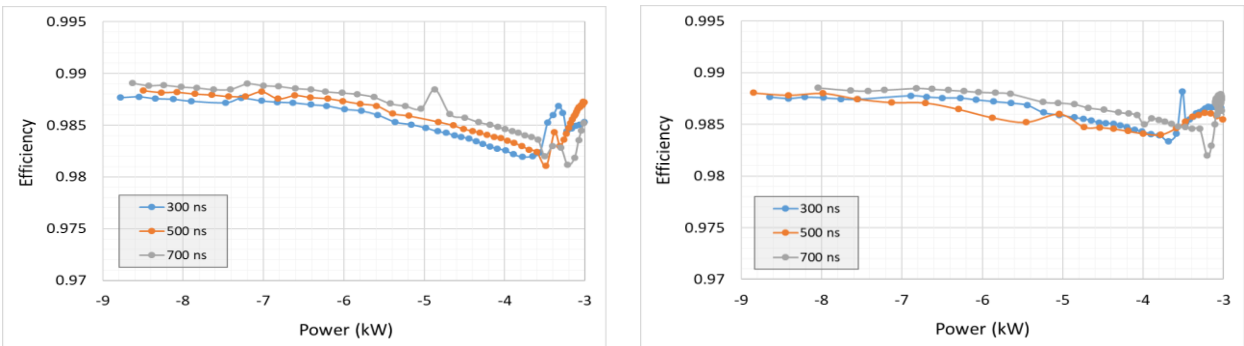


(a) (b)

Fig. 1: SiC based half-bridge converter; a) Hardware circuit implementation and b) Simulation.

Dead-time impact on performance of the SiC based DC-DC converter

To prevent shoot through in high and low side power devices in bridge configurations, dead-time is necessary. Shoot through can result in additional losses or thermal runaway. Typically, the dead-time is determined by taking into account turn on/off delay time, driver delay times and including some additional safety margin and such they can change with the operating condition. Whilst preventing shoot through, the inclusion of dead-time in a converter also impacts its performance. One way is that it causes output voltage disturbance and also low order harmonic distortion. On the contrary dead-time negatively impacts converter performance is from extra losses due to the freewheeling diode conduction. Since long dead times lead to longer body diode conduction and a consequent loss of efficiency, it is always desirable to provide an optimally minimized dead-time without running into shoot-through conditions. Due to characteristics of SiC device based converters, there are challenges related to the fixing the dead-time values. Turn-off time (t_{off}), which determines the dead-time, is affected by the operating circuit conditions. For instance, at different operating currents, the turn off time can be significantly different ranging from low to high load current. Hence having a traditional fixed dead-time depending on t_{off} determined by the worst operating point is not appropriate for SiC based converters. Therefore, a more adaptive approach to dead-time setting should be utilized in SiC based converter to ensure a good overall performance [5]. With powerful controllers used in automotive power electronics this is not considered an issue for implementation. Fig. 2 shows the variation of efficiency as a function of input power at different dead-times (300 ns, 500 ns, and 700 ns) for the SiC converter. The results demonstrates that even at this high frequency of 100 kHz the efficiency is over 98% for powers above 3 kW to approximately 9 kW.



(a) (b)

Fig. 2: Impact of dead-time on half-bridge converter with a) SiC Cree MOSFET with Parallel SiC Schottky diode, and b) SiC Cree MOSFET with its body diode.

A difference in conversion efficiency is observed as the dead-time is changed as depicted in Fig. 2. There are different explanations for this change in efficiency when dead-time increases and as can be observed the efficiency appears to be affected by the direction current. The reason is that the direction of current can have an effect on the duty ratio. For instance, when the inductor current (i_L) is positive, Q_2 and D_1 conduct and duty ratio increases with respect to the ideal switching case that has no dead-time (Figs. 3b and 3d). When the current is negative then Q_1 and D_2 conduct, then it appears to reduce the duty ratio (Figs. 3c and 3e). This is the reason that in the experimental result the efficiency of converter increased while the dead-time increased, because the inductor current is in positive direction and duty ratio increases, as shown in Figs. 2, 3b, and 3d. On the other hand, for lower current, in the low power range, the duty ratio is low, then the inductor current is in the border of being positive and negative, and current during the dead-time passes through both upper and lower diodes. When the duty ratio is high in order to operate on higher current and higher power range, then whole inductor current is positive (including its ripple), so the current during the dead-time passes only through one diode, which is the upper diode. This is another reason that effects the efficiency of the converter. Hence, this phenomena can be seen in the experimental result as a drop in efficiency around the 3 kW point, which can also be observed in Fig. 4.

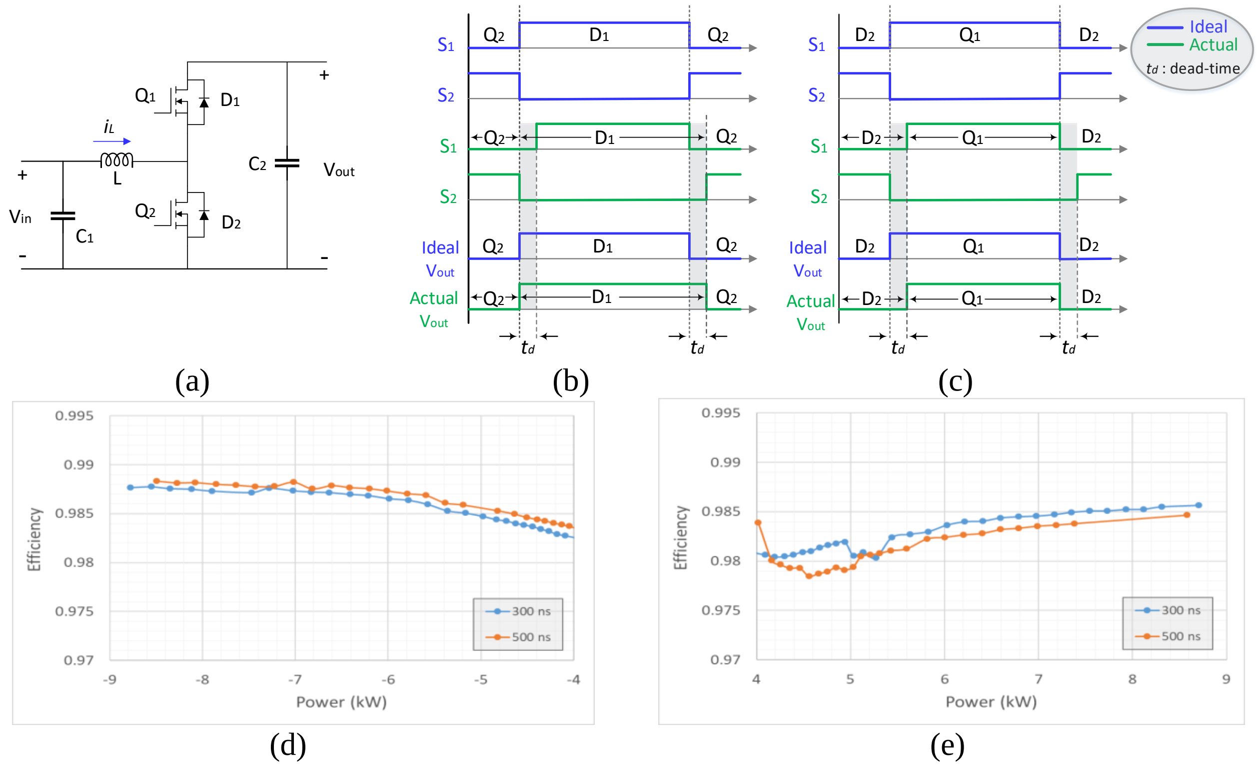


Fig. 3: Impact of dead-time on switching and efficiency of the converter; a) circuit diagram, b) positive i_L current, c) negative i_L current, d) experimental result of efficiency for positive i_L current, and e) efficiency for negative i_L current.

Impact of body diode

MOSFETs have the built in body diode. It is well known that these diodes have a reverse recovery, the peak of reverse current depends on forward current, slope di/dt (which can be find in the data sheet), and are dependent on operating temperature. Schottky diodes have negligible reverse recovery phenomena because it has no junction, however it has some capacitance which is nonlinear and it causes a small reverse current, as its capacitance vs reverse voltage curve can be seen in every data sheet. The consequence of this phenomena is two issues; power loss and parasitic oscillation. There are different solutions to overcome this problem. Such as using external parallel diode, using soft switching, or soft switching by using resonant converter. Using an external parallel diode which is a fast diode can work only if the voltage drop on parallel diode be smaller than the voltage drop on body diode ($V_{df} < V_{dm}$), because otherwise current goes through the body diode. A Schottky diode has a smaller voltage drop and is a good choice.

The subtlety of these effects is illustrated in Fig. 4 which shows performance at a fixed dead-time of 500 ns; the efficiency rises, falls and ultimately rises again as the power is increased in both boost and step-down modes. The reason for this behavior was explained in above paragraphs. As can be seen in figure the efficiency is not symmetrical in both side of axis. Again, the reason for the difference in efficiency is the direction of the inductor current and its impact on duty ratio. Therefore, in the left side of axis, which represents the step-down conversion, efficiency is a bit higher in comparison with the similar operating point of power on the right side of axis.

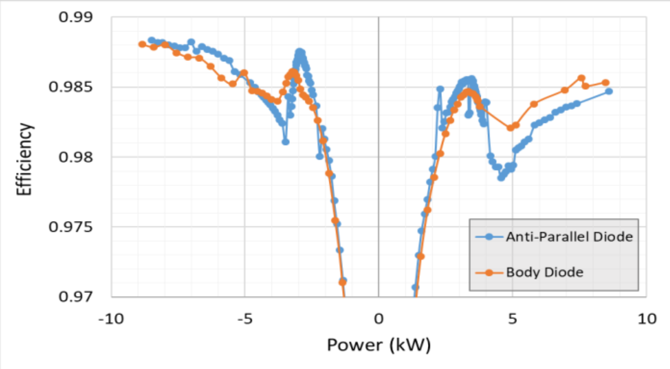


Fig. 4: Performance of SiC Cree MOSFET with anti-parallel SiC Schottky diode compared with SiC Cree MOSFET with its body diode, at 100 kHz switching frequency and 500 ns dead-time.

Conclusion

The performance of SiC power devices in a half-bridge circuit intended both for use in DC to DC conversion and as a building block for a traction converter was investigated experimentally. The power loss and efficiency of a half-bridge using SiC MOSFETs with and without an anti-parallel Schottky SiC diode has been compared as the dead-time is changed. A small difference in efficiency is seen as the dead-time is changed but there is a complex interaction between several factors that has been explained in this paper. For instance the current split between conduction paths provided by the MOSFET's channel, body diode and anti-parallel diode (if present) depends on the power level, input current direction, and differences in the relatively low device losses can be masked by changes in inductor losses. The results show that even at this high frequency the efficiency is over 98% for powers 3 kW to approximately 9 kW. The differences in efficiencies are about 0.1% to 0.3% at different operating points and conditions. However, in automotive applications, where high converter efficiencies are required, this change in efficiency can cause significant power losses.

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